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A review of uncertainty analysis in building energy assessment

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ABSTRACT

Uncertainty analysis in building energy assessment has become an active research field because a number of factors influencing energy use in buildings are inherently uncertain. This paper provides a systematic review on the latest research progress of uncertainty analysis in building energy assessment from four perspectives: uncertainty data sources, forward and inverse methods, application of uncertainty analysis, and available software. First, this paper describes the data sources of uncertainty in building performance analysis to provide a firm foundation for specifying variations of uncertainty factors affecting building energy. The next two sections focus on the forward and inverse methods. Forward uncertainty analysis propagates input uncertainty through building energy models to obtain variations of energy use, whereas inverse uncertainty analysis infers unknown input factors through building energy models based on energy data and prior information. For forward analysis, three types of approaches (Monte Carlo, non-sampling, and non-probabilistic) are discussed to provide sufficient choices of uncertainty methods depending on the purpose and specific application of a building project. For inverse analysis, recent research has concentrated more on Bayesian computation because Bayesian inverse methods can make full use of prior information on unknown variables. Fourth, several applications of uncertainty analysis in building energy assessment are discussed, including building stock analysis, HVAC system sizing, variations of sensitivity indicators, and optimization under uncertainty. Moreover, the software for uncertainty analysis is described to provide flexible computational environments for implementing uncertainty methods described in this review. This paper concludes with the trends and recommendations for further research to provide more convenient and robust uncertainty analysis of building energy. Uncertainty analysis has been ready to become the mainstream approach in building energy assessment although a number of issues still need to be addressed.

1. Introduction

Uncertainty analysis has received increasing attention in the field of building energy analysis [1–4] because a number of variables that influence building thermal performance are inherently uncertain, such as occupant behaviour, thermal properties of building envelope, and weather conditions [5,6]. Moreover, the development of modern uncertainty quantification techniques provides more advanced methods

Abbreviations: ACOSSO, Adaptive COmponent Selection and Smoothing Operator; ARIMA, Auto-Regressive Integrated Moving Average; ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers; BUGS, Bayesian inference Using Gibbs Sampling; CDF, Cumulative Distribution Function; DST, Demster-Shafer Theory; GIS, Geographical Information System; GP, Gaussian Process; GURA-W, Georgia Tech Uncertainty and Risk Analysis Workbench; HVAC, Heating, Ventilation, and Air Conditioning; IDF, Input Data File; LES, Least Square Estimation; LHS, Latin Hyper-cube Sampling; MARS, Multivariate Adaptive Regression Splines; MCMC, Markov Chain Monte Carlo; MLE, Maximum likelihood estimation; NREL, National Renewable Energy Laboratory; RBDO, Reliability Based Design Optimization; RDO, Robust Design Optimization; SMS-EMOA, S Metric Selection - Evolutionary Multi-objective Optimization Algorithm; SRC, Standardized Regression Coefficient; SRRC, Standardized Rank Regression Coefficients; TMY, Typical Meteorological Year; UKCP09, UK Climate Projections; UQ, Uncertainty Quantification

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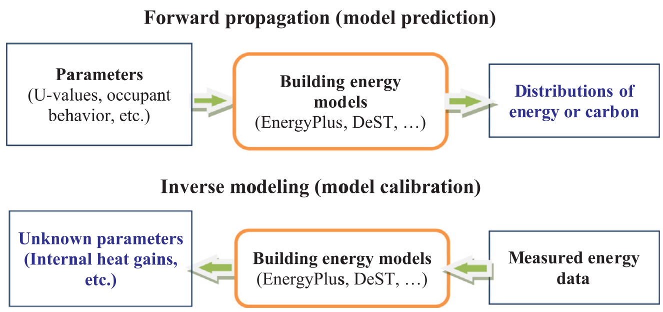

Fig. 1. Forward and inverse uncertainty analysis in building performance analysis.

and tools to facilitate the research on uncertainty analysis for a better understanding of the nature of building energy and associated energy models [7,8]. Therefore, uncertainty analysis has been widely implemented in various areas of building energy analysis, including model calibration [1,9], life cycle analysis [10–12], building stock analysis [13,14], impact & adaptation to climate change [15,16], sensitivity analysis [17,18], spatial analysis [19,20], and optimization [21,22].

Uncertainty analysis in building energy assessment can be divided into two categories as shown in Fig. 1: forward and inverse uncertainty quantification [23–25]. Forward uncertainty analysis (also called uncertainty propagation) focuses on quantifying the uncertainty in the system outputs propagated from uncertain input variables through mathematical models, while the purpose of inverse uncertainty analysis (also called model calibration) determines unknown variables through mathematical models from measurement data. From the perspective of building energy analysis, forward uncertainty quantification can predict energy use or carbon emissions using building energy models with input variations, whereas inverse uncertainty quantification can quantify unknown input variations through building energy models after collecting energy data from buildings. To date, considerably more research has been carried out on forward uncertainty propagation than on inverse uncertainty quantification in the field of building energy analysis. This is not surprising, as inverse uncertainty quantification is significantly more difficult than forward uncertainty propagation. Nevertheless, forward and inverse uncertainty analyses are closely linked [8]. Efficient forward uncertainty propagation is necessary for inverse uncertainty analysis because sampling-based inverse uncertainty analysis usually involves a large number of simulation runs [1]. The results from inverse uncertainty analysis are often used for forward uncertainty propagation to predict building energy use from various energy saving strategies [9,26].

A distinction is often made between two types of uncertainty: aleatory uncertainty and epistemic uncertainty [27,28]. Aleatory uncertainty (also called variability, stochastic, irreducible, and type A uncertainty) is due to inherent or natural variation of the system under investigation. In contrast, epistemic uncertainty (also called state of knowledge, subjective, reducible, and type B uncertainty) arises from a lack of knowledge. In building energy analysis, an example of aleatory uncertainty is occupancy presence, which can be better characterized from additional experiments or observation, but not be reduced as it is fundamentally impossible to predict variations of occupancy patterns for the future. Examples of epistemic uncertainty include lighting and appliance power densities, which can be better quantified by collecting more information to reduce its uncertainty, such as by installing measurement equipment for lighting and appliances. Note that not all of these uncertainties can be represented as specific probability functions (such as normal distribution, Gamma distribution, and uniform distribution). Aleatory uncertainty is naturally treated in a probabilistic framework, whereas epistemic uncertainty may be specified in a probabilistic or non-probabilistic way, including second order probability, interval, evidence theory, and fuzzy sets [28].

Researchers in the field of building energy simulation have proposed several classifications of uncertainty to represent the different characteristics of uncertainty in building energy analysis [3,22,29,30]. Uncertainty can be divided into model form uncertainty and parameter uncertainty [31,32]. Model form uncertainty (also called model discrepancy) refers to underlying the missing physics, numerical approximation, and other issues of computer programs [7,29], whereas parameter uncertainty refers to uncertainty associated with the values of parameter that appear in building energy simulation models. Uncertain parameters in building energy analysis can be further divided into three categories: design parameters, inherent uncertain parameters, and scenario parameters [3,22,30,33–35]. Uncertainty in design parameters exists in the design process where design parameters are determined through a series of design stages. For example, while the exact insulation materials or window types are not known in the early design stage, they will become known during the detailed design stage. Inherent uncertain parameters are usually uncontrollable, such as occupant behaviour, or the deviations between rated and actual plant system efficiencies. Scenario parameters refer to potentially varying economic or climatic conditions. Inherent uncertain parameters are usually denoted by normal distributions, whereas design uncertainty can be expressed by continuous or discrete uniform distributions [36]. Ramallo-González et al. [22] subdivided inherent uncertain parameters into workmanship & quality of building elements and occupant behaviour. Note that fewer studies have been carried out on model form uncertainty than on parameter uncertainty in the area of building energy analysis [37].

Although a large number of studies have been conducted on uncertainty analysis of building energy analysis, a comprehensive up-to-date review on uncertainty analysis in the area of building energy assessment is still unavailable. Therefore, this paper aims to provide a detailed systematic overview of uncertainty analysis in building energy assessment from four aspects: uncertainty data sources, both forward and inverse uncertainty methods, application of uncertainty analysis, and available software for uncertainty analysis. Because reliable uncertainty data are the foundation for uncertainty analysis in building energy analysis, it is necessary to gain a good understanding of the latest research development of data sources relevant to building performance as will be described in Section 3. Forward and inverse analysis (as will be described in Section 4 and Section 5, respectively) are the two main methods applied in the field of building performance assessment. The forward uncertainty analysis will discuss the Monte Carlo sampling-based, non-sampling, and non-probabilistic approaches to help an analyst choose the appropriate method. Inverse uncertainty analysis will be described from the perspectives of both the frequentist and Bayesian methods to provide a full picture of modern statistics to deal with the calibration problems of building energy models. Four applications on uncertainty analysis in building energy performance will be described in Section 6, including building stock analysis, HVAC system sizing, variations of indicators of sensitivity analysis, and optimization under uncertainty. The software available for uncertainty analysis will be presented in Section 7 to provide the computation environment for implementing the uncertainty methods described in this paper. Moreover, the trends and recommendations for further research will be summarized in the final section to provide more convenient and robust uncertainty analysis in assessing building energy performance. It should be emphasized that uncertainty analysis is not yet regarded as standard practice in assessing building performance in industry although the traditional deterministic approach is considered to be unacceptable due to the lack of sufficient information obtained from one single simulation run [38,39]. This review will also help to promote uncertainty analysis as a mainstream method in the area of building performance assessment.

2. Methodology

This literature review follows the concept-centric principle